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## On-Orbit Microwave Curing of Space Shuttle Repair Materials

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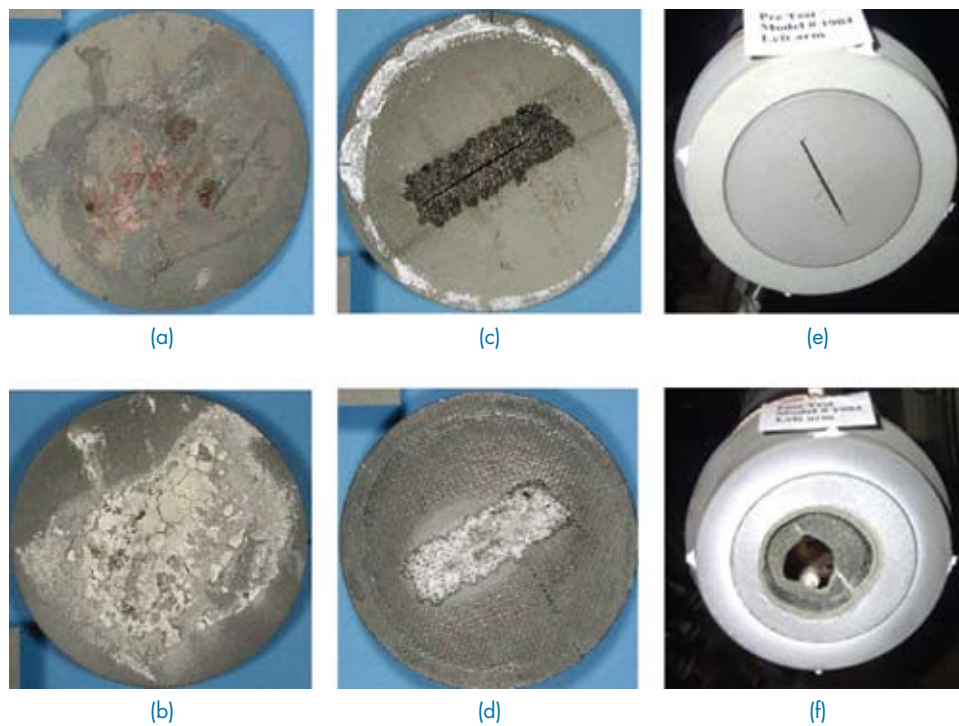
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**Introduction:** The loss on re-entry of the space shuttle *Columbia* on February 1, 2003, from launch damage to the reinforced carbon composite (RCC) wing leading edge has led NASA to require capabilities for shuttle on-orbit inspection and repair. NRL's Beam Physics Branch became involved with efforts to develop repair technologies for RCC materials through their expertise in microwave materials processing and microwave systems design and fabrication. Microwave sources are well suited for curing repair materials in the space environment because of their high electrical efficiency and ability to couple energy into repair materials volumetrically to provide rapid, localized heating. Alternative methods (heat lamp or a conductive heating blanket) were unsuitable because of inefficient surface heating with the heat lamp or difficulty in positioning the blanket in microgravity to obtain proper heating of the repair area without damaging the repair surface. The NRL team's investigation of on-orbit microwave curing of shuttle repair materials was carried out in collaboration with scientists at NASA Marshall Space Flight Center (MSFC), Huntsville, AL, and astronaut James F. Reilly II.

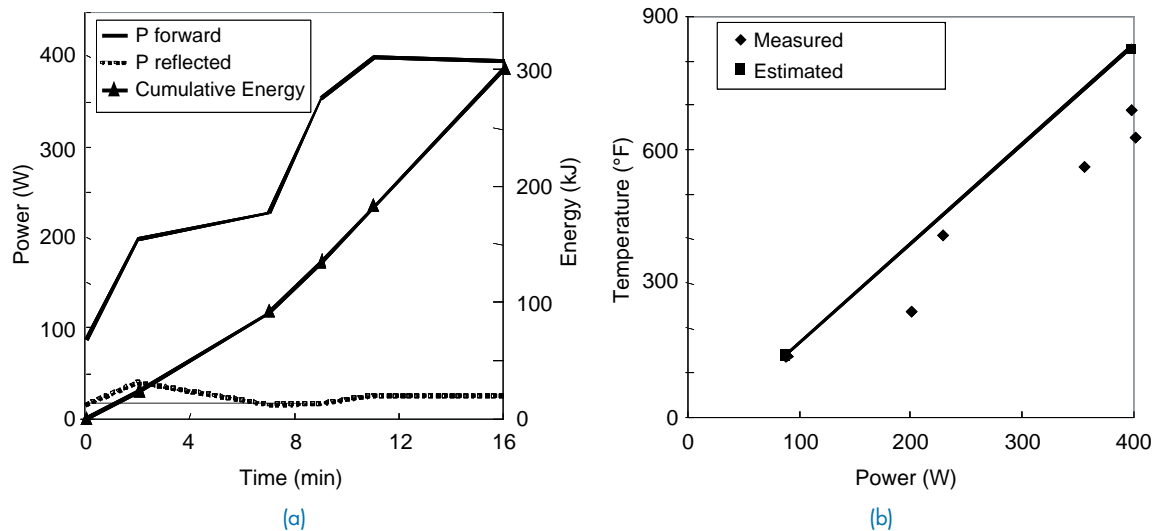
**Technical Approach:** Initial studies of applying microwave heating looked at the repair of fairly large damaged regions of the shuttle leading edge, but later work focused on the possibility of repairing small cracks and spalls, as these are the most common form of damage and are most amenable to astronaut repair on-orbit. Small cracks in the shuttle leading edge can be repaired by filling them with a material called Non-Oxide Adhesive eXperimental, or NOAX, a material developed by NASA consisting of a SiC precursor (hydridopolycarbosilane) filled primarily with SiC powder. It is designed to be applied by an astronaut using a space-adapted caulking gun and putty knife. The NOAX material couples well to 2.45-GHz microwaves; however, there is little microwave absorption by, or penetration into, the RCC material. To apply microwave heating, it was therefore necessary to use a microwave applicator capable of generating large microwave fields in the crack region. The NRL team used an approach previously developed for microwave joining.<sup>1</sup> This approach uses the fact that an electromagnetic

field polarized perpendicular to the crack direction can propagate into the NOAX-filled crack, which acts as a narrow dielectric-filled waveguide. The NOAX is heated by placing a simple microwave applicator, formed by tapering a standard rectangular S-band waveguide in the short dimension from 1.4 in. to 0.4 in., over the crack region. During heating, a three-stub impedance tuner placed upstream from the waveguide taper is adjusted to minimize the reflected power, thus optimizing the microwave coupling to the NOAX. Initial tests to determine the power requirements and heating protocols needed to cure the NOAX used an industrial 6 kW, 2.45 GHz magnetron. Microwave absorption by the NOAX was found to be temperature dependent, with a marked decrease occurring after pyrolyzation sets in at 800 °F, a feature that can be used as an indication of process completion. Several analog RCC samples with NOAX-filled cracks were prepared at NASA/MSFC in a vacuum glovebox, delivered to NRL by astronaut Reilly for microwave processing, and then shipped to St. Louis, MO, for successful testing in the Boeing arcjet facility. Photographs of repaired and untreated crack-containing samples are shown in Fig. 1. A typical heating protocol is shown in Fig. 2.

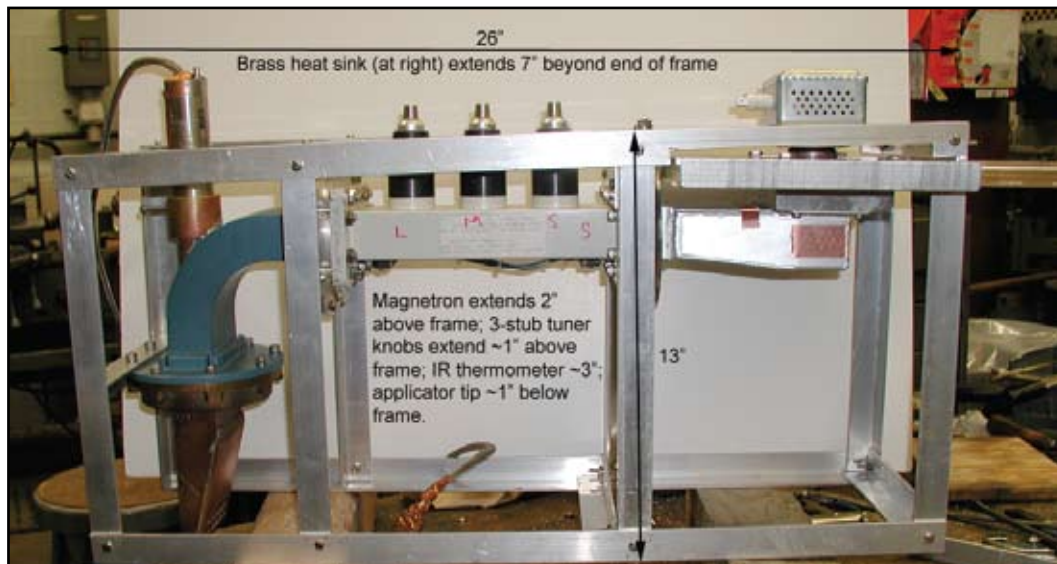
**Prototype Development:** Based on these studies, a brassboard microwave curing system (MCS) was designed and fabricated (Fig. 3). This system consists of a commercial off-the-shelf (COTS) magnetron and power supply, a tuner (for impedance matching) and the applicator. Discussions with extra-vehicular activity (EVA) tool designers at NASA Goddard Space Flight Center, MD, and Swales Aerospace, MD, made clear the necessity for compactness and ease of use by space-suited astronauts. A procedure requiring few adjustments during processing was sought. In the initial tests, the tuner was continually adjusted to minimize the reflected power. In prototype tests it was found that a single tuner setting could often be used. The overall efficiency of the magnetron and power supply was found to be about 65%, leading to thermal loads in the range of 200–400 W for output powers of 0.5–1 kW. Addressing the needs of the space environment, the magnetron convective air-cooling system was replaced by a metal heat sink. The prime power and energy storage requirements can be easily provided by a compact battery pack. Microwave leakage from the applicator was a concern, but a small skirt of wire-mesh screen placed around the applicator tip reduced this to milliwatt levels. Preliminary tests of operating in the vacuum environment were conducted in a large vacuum chamber/glove box at NASA/MSFC shortly before the end of the program. These tests confirmed the feasibility of the microwave processing approach, provided that the microwave power is restricted during

**FIGURE 1**

Successful arcjet tests of microwave-cured samples (simulated crack damage in RCC analog). (a), (c) Front and back before test. A crack has been cut through the sample with SiC coating removed, on back. (b), (d) Microwave-cured NOAX crack repairs survive arcjet testing. (e) Unrepaired RCC (no NOAX), and (f) catastrophic burnthrough after arcjet testing.

**FIGURE 2**

(a) Power and energy profiles. (b) Temperature vs microwave power.



**FIGURE 3**  
Brassboard system in aluminum frame for glove box tests.

initial heating to avoid plasma formation associated with NOAX outgassing.

This technology has demonstrated the ability to heat RCC repair materials in vacuum, and may also have land- and sea-based applications for rapid, in-situ repair of military systems such as aircraft that make use of RCC materials.

[Sponsored by NASA and ONR]

#### Reference

- <sup>1</sup> S.H. Gold, D.A. Lewis, A.W. Fliflet, B. Hafizi, and J.R. Peñano, "Interference and Guiding Effects in the Heating of Ceramic Slabs and Joints with Millimeter-Wave Radiation," *J. of Materials Synthesis and Processing* **9**, 287-297 (2002). ◇